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THE PERFORMANCE OF N/P SILICON AND CdS SOLAR CELLS AS EFFECTED BY SIMULATED MICROMETEROROID EXPOSURE

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TECHNICAL PAPER prepared for presentation at Sixth IEEE Photovoltaic Specialists Conference to be held at Cocoa Beach, Florida, March 28-30, 1967

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The results of recent satellite experiments on Relay I and II (ref. 1) indicate that unshielded N/P silicon solar cells degrade to approximately 50 percent of their initial short circuit current in 4 days. In addition this experiment showed that by using 30 or 60 mill quartz cover plates the degradation was reduced such that the current fell to only 95 percent of its initial short circuit current in the same 4 days, indicating that cover plates effectively protected the silicon solar cells. For both the covered and uncovered case, the reduction in cell performance was attributed solely to the radiation environment in space. The improved performance of the quartz-covered cells was explained by absorption of harmful radiation by the covers. Considerable subsequent research has been devoted to developing radiation resistant cells (refs. 2, 3), with either very thin, integral glass cover plates (ref. 4) or semiorganic spray coatings (ref. 5) to reduce system weight. However, very little attention has been given to possible deleterious effects on cell performance resulting from bombardment by the high speed micrometeoroids in near-earth space. Therefore the work reported herein was undertaken to investigate and isolate, in a preliminary fashion, such possible effects by exposing both uncovered and covered N/P silicon solar cells and encapsulated CdS solar cells to a simulated high speed micrometeoroid environment. This information can then be compared with other ground experiments involving radiation environmental effects in order to determine relative damage resulting from the two environments. For the silicon cells, an attempt is then made to relate real time-in-space with the degradation in cell performance obtained by the simulated exposure. The effects of the two environments simultaneously can then be compared, at least qualitatively, with the satellite solar cell performance experiments that have been flown in the actual total environment, but on which no attempt was made to separate the two effects. Hopefully clarification of these effects will reduce the possibility of oversight wherein cells are developed and flown impervious to one factor, but rapidly degradable by the other.

In the experimental program, unshielded and shielded 1×2 centimeter N/P silicon solar cells (with cover plates of various types and thickness) and CdS solar cells (encapsulated in 1 mil thick H-film and mylar) were bombarded by clouds of 6μ diameter SiC particles accelerated to hypervelocities in a shock tube. The number, size and velocity of the particles were measured so that total kinetic energy of the cloud of particles could be used to characterize the exposure (ref. 6). The particle clouds of 6μ SiC were of sufficient velocity (2.65 km/sec) to simulate hypervelocity impact in metals (ref. 7). However, for solar cells, since no criteria exist for designating the minimum particle speeds required for hypervelocity impact on any of the surfaces exposed to the particles in the present study, it was assumed here that this velocity would be sufficient.

The degradation of the solar cells was determined by measuring the current-voltage characteristics of the cells both before and after exposure to the particle clouds. The characteristic curves were measured at an intensity of one solar constant (140 mw/cm^2) in the carbon arc solar simulator described in reference 8. A calibrated thermopile was placed next to the solar cells to monitor the beam intensity during the test and the cells were water cooled to maintain a constant cell temperature of 25° C. Typical characteristic curves of an unprotected N/P silicon solar cell for total bombardment exposure energy varying from 0 to 0.316 joules are shown in figure 1. It will be noticed that the degraded cells exhibit a rather steep linear characteristic. Thus, the load resistance used in the cell circuit becomes a critical parameter when the cell output current is used as an indication of unprotected silicon solar cell degradation. Hence, our data are presented at true short circuit conditions; i.e., zero load resistance.

Typical characteristic curves of a CdS solar cell encapsulated in 1 mil mylar for a total bombardment exposure energy varying from 0 to 2.02 joules are shown in figure 2. It will be noticed that the shape of the CdS curves, unlike those of the unprotected N/P silicon solar cells, remain the same with increasing exposure energy. Although not presented herein, the characteristic curves of bombarded H-film encapsulated CdS cells behave in a similar fashion. It should be mentioned that great care was taken to protect the CdS cells from the effects of moisture (ref. 9) by keeping them in a desiccator when not in use and a N_2 filled dry box when obtaining characteristic curves with the carbon arc simulator. In addition, frequent checks on the characteristic of a standard cell were made throughout the experimental program and no effect of moisture was found. There were also no effects of the shocked gas flow alone, encountered in the shock tube, on the performance of the solar cells investigated.

In figure 3 the ratio of final to initial short circuit current (measured at one solar constant) is presented as a function of the total kinetic energy of the cloud of bombarding particles. It can be seen that at 0.1 joule exposure the short circuit current for the unprotected N/P silicon cells has dropped to approximately 40 percent of its initial value, and that at 0.2 joule the current has dropped further to 15 percent of its initial short circuit value. However, the silicon solar cells with protective cover plates of 6 mil microsheet, 21 mil quartz, 62 mil quartz, and 60 mil sapphire, exhibit relatively little damage (95% of initial short circuit at one-half joule) when exposed to the same kinetic energy of particles. An increase in thickness or a change of material apparently afforded no further protection for the solar cell at a given exposure.

The CdS solar cells encapsulated in 1 mil thick mylar exhibited about the same rate of reduction in short circuit current as the protected N/P silicon solar cells (fig. 3). However, the reduction in short circuit current of the 1 mil H-film encapsulated CdS solar cell was greater than that of the mylar encapsulated CdS cell when exposed to the same kinetic energy of particles. Actually 80 percent of initial short circuit current was obtained for the H-film encapsulated CdS at an exposure of 1 joule compared to 87 percent for the mylar encapsulated CdS cell at the same exposure. Many other mylar and H-film encapsulated CdS solar cells were used in the experimental program and all exhibited reduction in short circuit current similar to the ones presented in figure 3. These results, of course, do not preclude the possibility of significant damage due to use of semiorganic coatings, other plastics or cover plates whose thickness are less than those tested.

In order to relate the laboratory degradation of cell performance to that obtained in space for comparison with some actual satellite data, a conversion of laboratory exposure in joules to actual time in space is required. Only N/P silicon solar cells will be compared since CdS solar cells have not as yet been tested in space. Of course, the parameter chosen for comparison must be obtained at the same operating point, e.g. the true short circuit current condition. This latter requirement is not always fulfilled. For example, on the Relay I and II satellite experiment, each solar cell was loaded initially to give a voltage of about 165 millivolts in space sunlight. If one assumes an initial short circuit current of 70 milliamps for an ideal undamaged silicon solar cell as in reference 10, then the minimum load resistance was approximately 2.35 ohms. As a result of the constant high resistance used and the fact that linear characteristics are obtained from degraded silicon cells (fig. 1) the Relay I and II data presented in reference 1 for unprotected cells are, in all probability, not representative of short circuit conditions. In fact, since the linearity of the degraded cells apparently changes, short circuit conditions are not even approximated in a consistent fashion. This, of course, makes quantitative comparisons with ground studies very difficult. Consequently the comparison of the space data with the laboratory data presented herein for unprotected silicon cells can only be considered qualitative since the laboratory degradation is in terms of the true short circuit current. It should be noted that Relay I and II data below the 50 percent degradation point are not presented herein since Waddel (ref. 1) points out that beyond this point the data are questionable.

The conversion of exposure to actual time in space requires knowledge of the micrometeoroid environment of near-earth space. The micrometeoroid microphone impact flux data of reference 11 as well as the geocentric micrometeoroid flux model of reference 12 were used to estimate the conversion factor. One simple function does not continuously describe the data of reference 11 between the mass range of 10^{-8} to 10^{-12} gram (i.e., the microparticle range). Therefore, the distribution curve was broken up into three mass ranges and representative flux distribution functions determined for each mass interval. To obtain the total mass M_T falling on a 1×2 centimeter solar cell the flux distribution function was integrated over these mass intervals and the results are shown in table I. For an average particle velocity of 30 kilometers per second, as in reference 11, the total kinetic energy for a given mass range, was calculated and is shown in column 5 of table I. Thus, if the meteoroid mass distribution curve of reference 11 is correct, the total kinetic energy of particles in the mass interval 10^{-8} to 10^{-12} gram falling on a 1×2 centimeter solar cell in 1 year is 4.95 joules.

A revised geocentric meteoroid mass-flux curve, that includes data obtained both with microphone and penetration systems, is presented in figure 3 of reference 12. The flux distribution function is shown in table I. Upon integration of this curve between the limits 10^{-8} and 10^{-12} gram and assignment of a particle velocity of 7.35 kilometers per second (as in ref. 12) one finds that the total kinetic energy of particles falling on a 1×2 centimeter solar cell in 1 year is 0.225 joule; a value considerably lower than that obtained utilizing the data of reference 11. However, as pointed out in reference 13, the laboratory exposure energy cannot simply be replaced by the space energy to determine equivalent time in space. The total conversion must account for the difference in single particle kinetic energy. By using the energy scaling method of reference 13, assuming the most numerous (minimum size) particle in space to be 10^{-12} gram, and the micrometeoroid flux of reference 11, $\epsilon_S = 0.752\ \epsilon_L$ for equal damage and hence 0.018 laboratory joule equals one space day (6.57 lab joules = 1 space year). The same calculation using the geocentric meteoroid mass-flux curve of reference 12 yields $\epsilon_S = 0.295\ \epsilon_L$ and for this flux model 0.0021 lab joules is equivalent to one space day (0.762 lab joule = 1 space year) for equal damage.

Using these time-laboratory kinetic energy conversions, the expected damage from micrometeoroids in space to unprotected N/P silicon solar cells is compared in figure 4, with the Relay I and II data (shown as the solid lines) of reference 1. Comparison of the satellite data with the determinations estimated for the micrometeoroid environment of reference 11 indicates that the initial damage could be due to micrometeoroids alone. Since the load resistance used in reference 1 was high and the cell characteristic degrades as shown in figure 1, the current ratio presented in reference 1 is, in general, low. As a result, the Relay data if corrected for these effects should be in much closer agreement with the curve predicted using the data of reference 11. On the other hand, if the flux function of reference 12 is used, it could then be concluded that, after 4 days in space, most of the reduction in performance of Relay I and II solar cells was due to radiation rather than micrometeoroids. It will be noticed that an unprotected N/P silicon solar cell will degrade to 50 percent of the initial short circuit current in about four space days from the micrometeoroid environment of reference 11. On the other hand, if the flux function of reference 12 is used as representative of the micrometeoroid environment and extrapolated beyond 4 space days an unprotected N/P silicon solar cell will degrade to 50 percent of its initial short circuit current in about 34 space days. Both of these times, although differing by a factor of 8, are short for any near earth space mission using unprotected solar cells as a power supply and indicate that this type of cell must be protected from the near earth micrometeoroid environment.

Figure 5 presents the ratio of the final to initial short circuit current for protected (30 mil cover plate) N/P silicon solar cells of Relay I and II against time in space. Also presented, for comparison purposes, is the expected damage to protected solar cells due to the micrometeoroid environment of near-earth space. These curves were again found by converting the laboratory imposed damage of figure 3 for protected solar cells to real time in space, using the methods of the previous paragraphs. The figure shows that, for both the micrometeoroid flux data of references 11 or 12, a solar cell with any of the cover plates used herein would suffer negligible damage in 4 days due to micrometeoroids alone, when compared to the unprotected N/P silicon solar cells. In 55 days, the solar cell current would be reduced to 0.90 of the initial current due to the micrometeoroid environment of reference 11 alone. This degradation is somewhat less but of the same order as that suffered by the Relay I and II protected solar cells. For the geocentric micrometeoroid flux model of reference 12, there is very little damage suffered (about 1% reduction in $I_{SC\,initial}$) in 55 days from micrometeoroids alone. The degradation of the protected N/P silicon solar cells in space could then be due primarily to the radiation environment near the earth.

In summary, results of the present ground study of degradation of protected and unprotected solar cells bombarded by simulated micrometeoroids indicate the following:

1. Micrometeoroid damage to N/P silicon solar cells covered by the thinnest glass sheets that were used (6 mils) was greatly reduced from the damage obtained from cells without cover plates. Changing the cover material to quartz or sapphire, or increasing thickness to 60 mils gave no additional protection. Unprotected N/P silicon solar cells were degraded rapidly by simulated micrometeoroid bombardment.

2. A mylar encapsulated CdS solar cell will perform in a micrometeoroid environment as well as a N/P silicon solar cell protected by a 6 mil cover sheet. Mylar (1 mil) encapsulated CdS solar cells affords more protection from micrometeoroid bombardment than H-film (1 mil) encapsulated CdS solar cells.

3. The conclusions drawn from a comparison of laboratory results with satellite results depend heavily on the micrometeoroid flux distribution chosen as representative of the micrometeoroid environment. Although the comparison is not yet definitive due to the uncertainty in the choice of micrometeoroid flux model, it indicates that protection of solar cells from micrometeroroid damage may be as improtant as protection against radiation damage. This suggests that integral covers of very thin coatings which protect against radiation, may not be adequate to protect the cell against micrometeoroids.

SYMBOLS

A area

E_i $1/2\ M_T v^2 A$, joules/yr, total kinetic energy of a cloud of particles in space falling on a (1×2) cm area

$\dot{F}_i$ flux distribution function for a given particle mass interval
I_{SC} short circuit current
M_T total mass falling on a given area
m particle mass
v particle velocity
ϵ $\sum_i^N 1/2\, m_i v_i^2$, joules, total kinetic energy of a cloud of particles hitting a 1 × 2 cm area

Subscripts

L laboratory
S space

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Figure Title List

Figure 1. Typical Characteristic curves of an unprotected N/P silicon solar cell before and after exposure to $(\bar{6})\mu$ SiC particles at 2.65 km/sec

Figure 2. Typical characteristic curves of a CdS solar cell encapsulated in a 1 mil mylar film before and after exposure to $(\bar{6})\mu$ SiC particles at 2.65 km/sec

Figure 3. Plot of ratio of final to initial short circuit current for 1 × 2 cm silicon and CdS solar cells against kinetic energy of cloud of impinging $(\bar{6})\mu$ SiC particles at 2.65 km/sec in the laboratory

Figure 4. Plot of ratio of final to initial short circuit current against time in space for unprotected N/P silicon solar cells

Figure 5. Plot of ratio of final to initial short circuit current for protected N/P silicon solar cells against time in space

TABLE I

Mass range, g	Flux distribution function	$M_T = \int m\, dF$, g/m^{2}sec	$E_i = \frac{1}{2} M_T v^2 A$ joules/yr for 2cm^{2}cell	$E_T = E_1 + E_2 + E_3$ joules/yr for 2cm^{2}cell
Reference 11				
10^{-8} to 10^{-10}	$F_1 = 10^{-17}\ m^{-1.7}$	2.3×10^{-10}	$E_1 = 0.67$	---------
10^{-10} to 10^{-11}	$F_2 = 2.2\times10^{-11}\ m^{-1.1}$	6.05×10^{-10}	$E_2 = 1.67$	$E_T = 4.95$
10^{-11} to 10^{-12}	$F_3 = 10^{-7}\ m^{-0.8}$	9.5×10^{-10}	$E_3 = 2.61$	---------
Reference 12[a]				
10^{-8} to 10^{-12}	$F = 10^{-27.05}\left(\frac{r}{7380}\right)^{-2} m^{-(4.103+0.1368 \log m)}$	13.2×10^{-10}	---------	$E_T = 0.225$

[a] With latest revision of coefficient and exponent values supplied by the authors of reference 12.

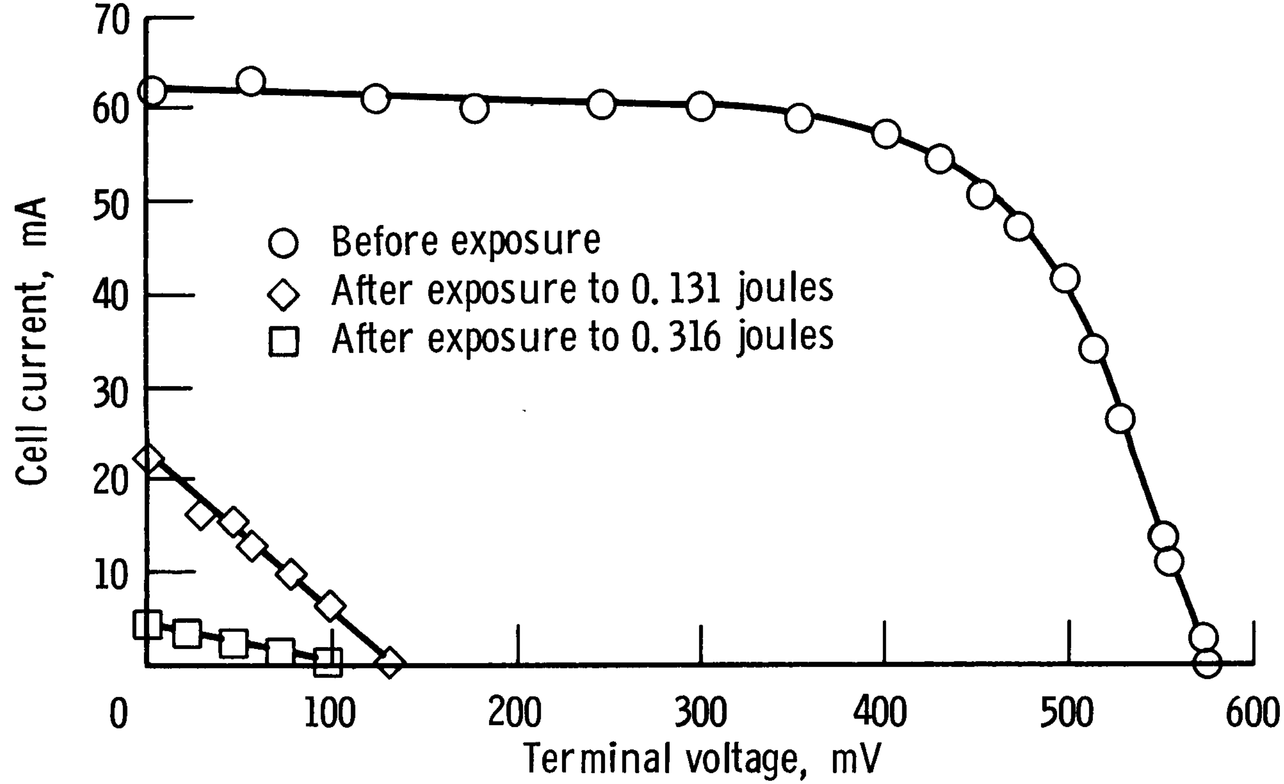

Figure 1. - Typical characteristic curve of an unprotected N/P silicon solar cell before and after exposure to $(\bar{6})\mu$ SiC particles at 2.65 km/sec.

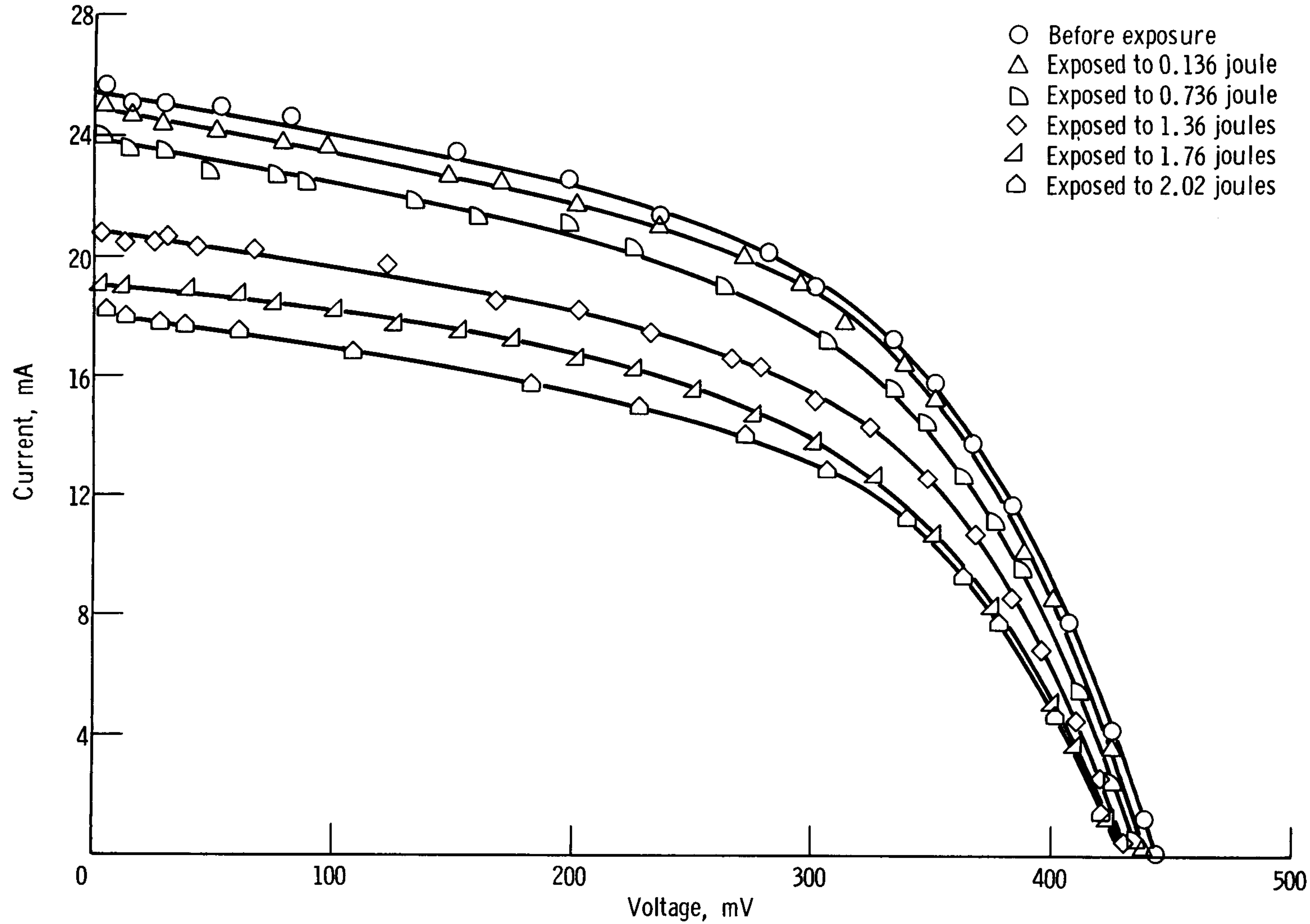

Figure 2. - Typical characteristic curve of a CdS solar cell encapsulated in a 1 mil Mylar film before and after exposure to (6)μ SiC particles at 2.65 km/sec.

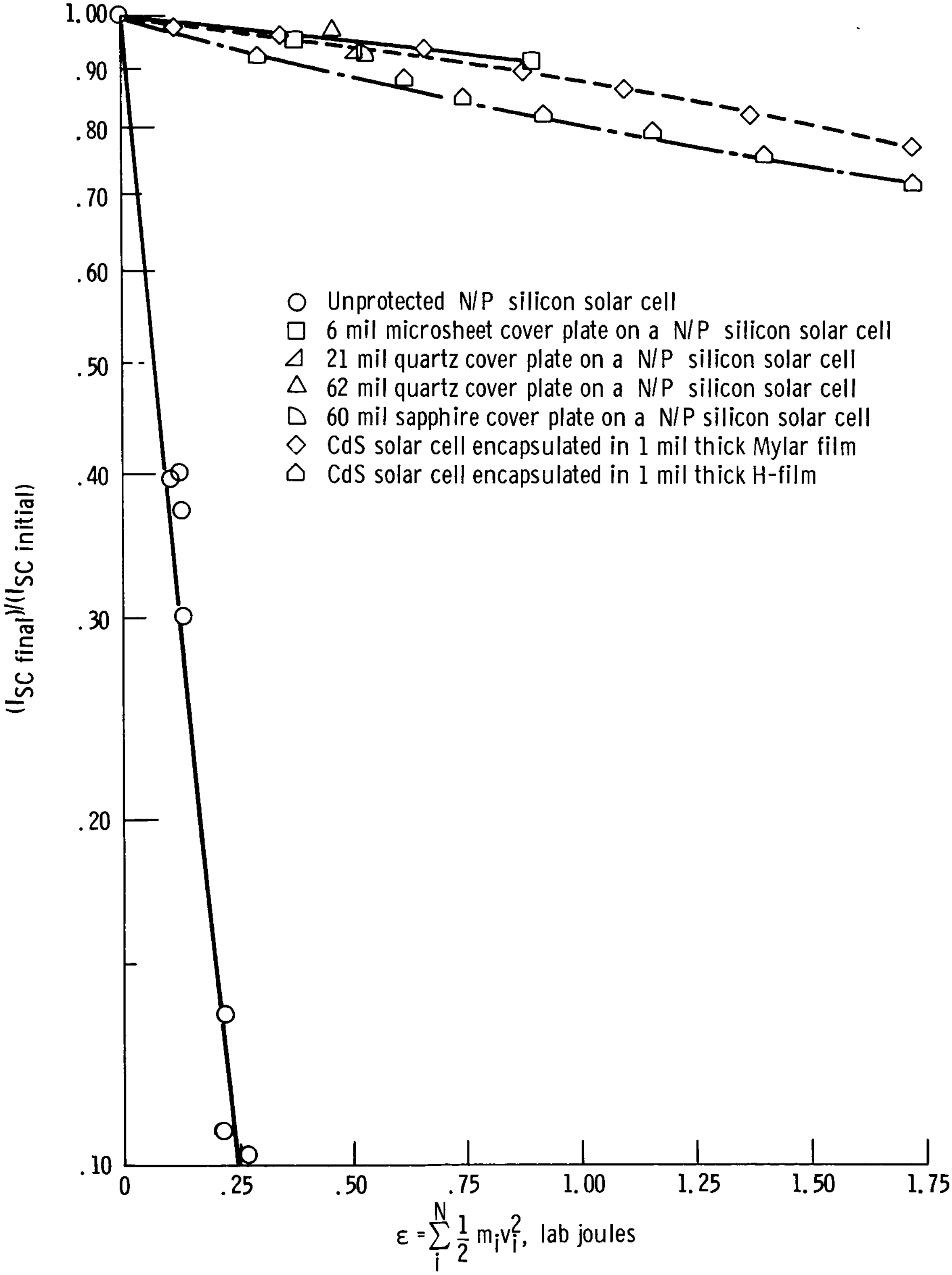

Figure 3. - Plot of ratio of final to initial short circuit current for 1x2 cm silicon and CdS solar cells versus kinetic energy of cloud of impinging $(\bar{6})\mu$ SiC particles at 2.65 km/sec in the laboratory.

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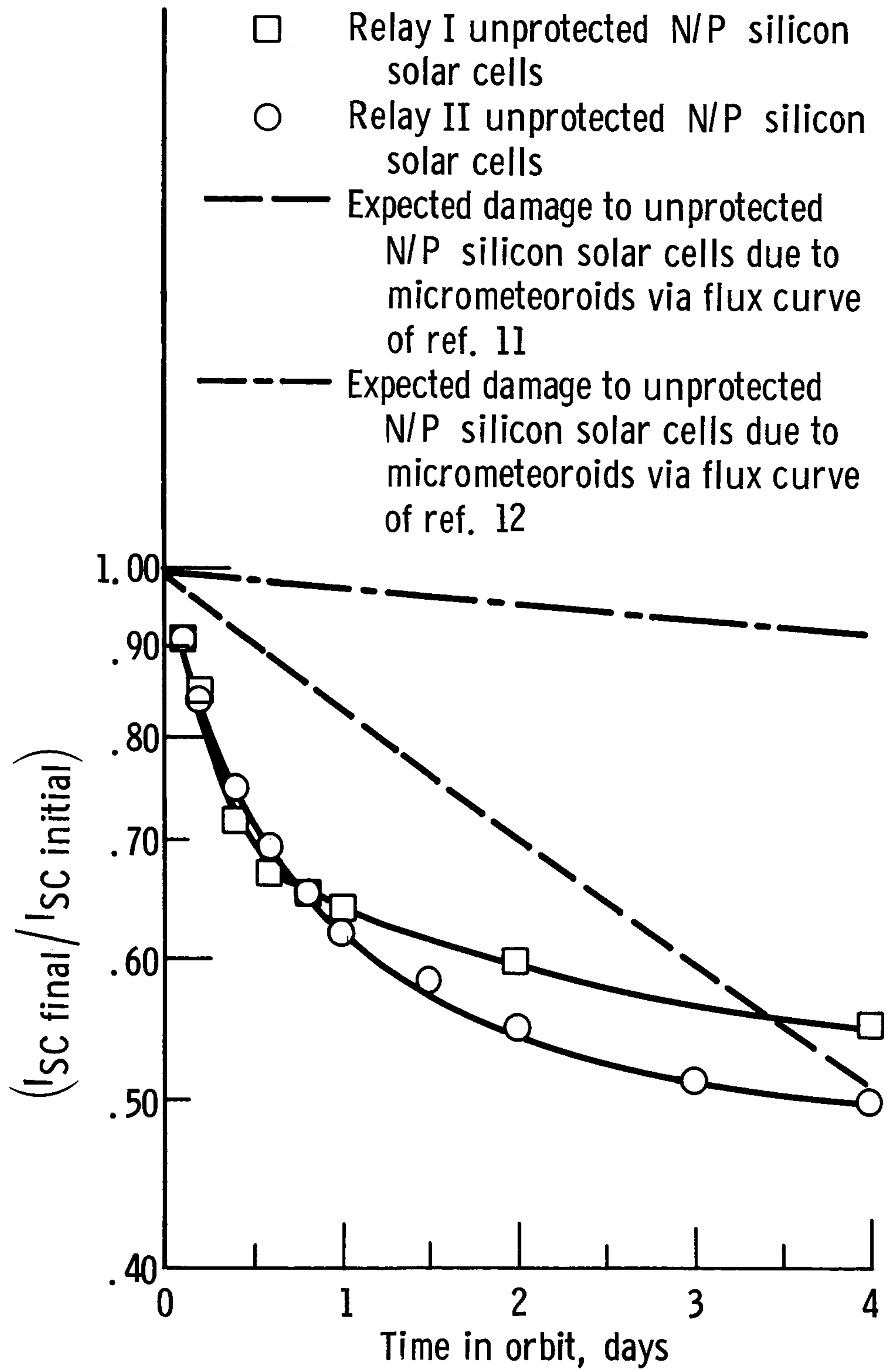

Figure 4. - Plot of ratio of final to initial short circuit current versus time in space for unprotected N/P silicon solar cells.

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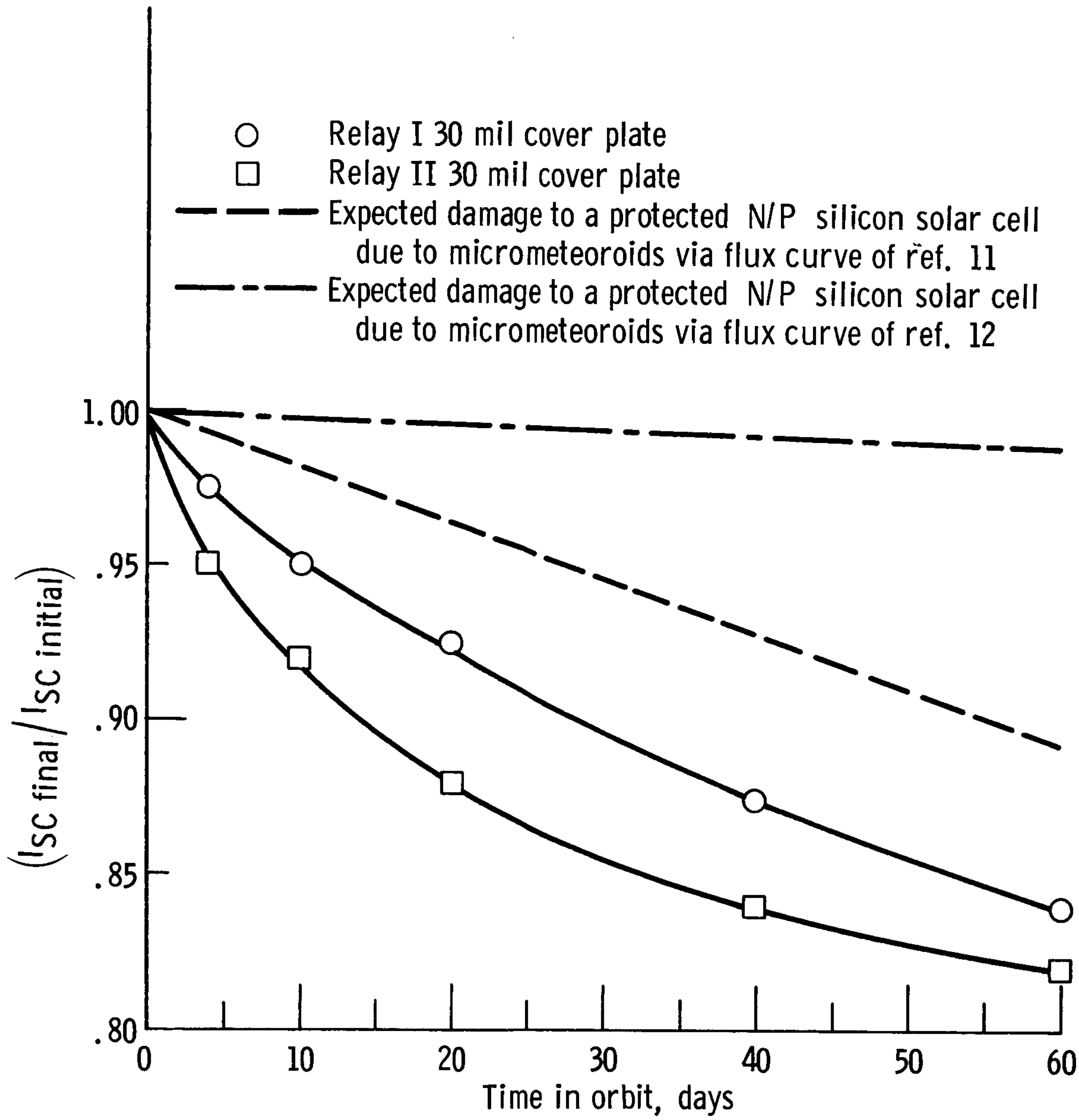

Figure 5. - Plot of ratio of final to initial short circuit current for the protected N/P silicon solar cells versus time in space.

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